Appendix B. Cost and Performance as a Function of Energy

C. M. Ankenbrandt and R. P. Johnson

Summary

Alternative Proton Drivers (PD) with different maximum energy, magnet aperture, and injection strategies are examined. It is found that lower energy designs with smaller ring circumference can provide construction and operation cost savings. Using the cost of the machine components as shown in Appendix A, the cost of each alternative PD is derived by using scaling laws. The most important scaling law is that the cost of magnets and magnet resonant power supply systems should scale as the stored magnetic energy in the accelerator. The next most important scaling factor is the RF power, effectively the number of RF cavities, which increases with ring circumference and with energy swing. The reduced circumference of a lower energy ring allows Stage 1 MI injection requirements to be met with the present Linac and H^- source by virtue of more batches. A less expensive method to achieve the Stage 2 power on target for a lower energy machine would be to improve the H^- source and raise the injection Linac energy. Other performance and construction issues are discussed and costs for alternative proton drivers of 8, 12, and 16 GeV are derived.

B.1. Introduction

In this Appendix, plausible alternative energy Proton Drivers (PD) are described that should have performance equal to the 16 GeV machine described in the main body of the report. That is, for Stage 1 (MI Operation) at least 1.2×10^{14} protons must be injected into the MI. In Stage 2 (Neutrino Factory) there should be 1 MW of beam power. In all cases, the calculated Laslett tune shift should be the same or less than that in the baseline Proton Driver (bPD).

Using a simple spreadsheet, three studies are described which demonstrate the consequences of certain parameters choices.

In the first study, machines of 8, 12, and 16 GeV maximum kinetic energy (T_{max}) with 40π mm-mrad transverse acceptance are modeled to show how their costs compare to each other and to the 16 GeV 60π baseline design. These energies are chosen because 8 GeV is considered the lowest energy compatible with present Booster functionality, 16 GeV allows a comparison between two different transverse acceptances, and 12 GeV, besides being midway between the other two, is the actual Stage 1 energy of the bPD. The 8, 12, and 16 rings with 40π acceptance have, respectively, circumferences of ¾, 1, and 1.5 times that of the present Fermilab Booster.

The strength of the comparison is that general cost scaling arguments can be used to get rather good relative values for components. Two of the most important scaling parameters turn out to be stored energy in magnet and power supply systems and rf power. These are found to dominate the cost comparisons. Machines of lower energy, smaller circumference, and smaller transverse acceptance are therefore favored, providing they can satisfy the Stage 1 MI intensity and Stage 2 beam power requirements. Where needed, these requirements are accomplished by increasing the Linac energy and H^- source capabilities. Costs for the needed injector improvements are estimated and included in the comparisons.

The second study is a comparison of operating costs for the 40π model machines at 8, 12, and 16 GeV and the 60π baseline PD.

The third study is to compare the costs for an 8 GeV machine of Fermilab Booster circumference as a function of B_{max}, the maximum dipole field. The study indicates that the cost savings for a lower B_{max} can offset the increased rf and conventional construction costs associated with a larger circumference.

B.2. Important Parameters

B.2.1. Laslett space charge tune shift

The Laslett incoherent space charge tune shift or spread,

$$\Delta\nu = \frac{3 f_T r_P}{2B} \frac{N_P}{\beta\gamma^2 \varepsilon_N} \tag{B.1}$$

is used as the touchstone in all the accelerator models discussed below and allows the parameters of the machines to be varied in a consistent manner. Here B and $f_{T,}$ the bunching and transverse form factors, and Δν are defined to be the same as used for the baseline PD design. The number of protons (N_P), the beam normalized transverse emittance (ε_N), and the injection energy (which determine the Lorentz parameters of β and γ), are the variables used to equalize performance parameters of MI intensity (Stage 1) and beam power (Stage 2) for each design. The relativistic Lorentz factor βγ for 400 MeV kinetic energy is 1.02 so the geometrical acceptance, $\varepsilon_{G,}$ is very nearly the same as the normalized emittance, $\varepsilon_N = \beta\gamma\, \varepsilon_G$.

B.2.2. Circumference

One important parameter, which is not in the Laslett tune shift formula, is the machine radius or circumference. The maximum number of protons that can be stored in a ring limited by the Laslett tune shift is independent of the circumference of the ring. This fact can be used in the design of the 8 and 12 GeV machines, which can have a smaller circumference than the 16 GeV baseline machine. With more batches (PD beam acceleration cycles) to load the MI, each batch can have fewer protons, allowing the transverse acceptance to be smaller with the same Laslett tune shift.

Of course, fewer batches means that the MI can be loaded faster, which in the case of the 4-batch injection of the baseline PD implies a 7% increase in protons per hour for MI operation compared to the 6-batch injection from a ring of Booster circumference. On the other hand, a ring with circumference larger than that of the present Booster cannot efficiently create and store antiprotons in the Booster-sized Antiproton Accumulator. One third of the batch destined to hit the antiproton production target from the baseline PD should be without beam in this case, and if there were three other batches, this would lead to an 8% decrease in protons/hr from the MI.

Synchrotrons of smaller circumference will also have a smaller transverse beam size and require less magnet aperture since each transverse beta function scales as the square root of the radius.

Fewer rf cavities are needed as the circumference is reduced, since the beam passes through the cavities more often. Fewer cavities are needed, as well, if the machine energy is reduced such that the maximum dE/dt is lowered. Approximately, then, a ring of half the energy and half the circumference will require a quarter as many rf cavities.

Since the fraction of the circumference occupied by rf in a smaller, lower-energy machine is also reduced, the fraction of the ring used for other things can be increased. This means, for example, that a larger packing fraction (total bending magnet length/circumference), or more complex lattice design is easier to accomplish. As discussed below in the third study, a larger packing fraction can be used to reduce costs by reducing the B_{max} and lowering the stored energy in the magnet and power supply systems. A lower B_{max} also has the virtue that magnet saturation and induced dipole and quadrupole tracking problems are reduced.

B.2.3. Injection Energy and Intensity

For the alternative Proton Drivers in this Appendix, the choice has been made to rely on upgrading the existing H^- source and the Linac to provide more protons for Stage 2 beam power or to provide more energy to reduce the Laslett tune shift at injection by increasing $\beta^2 \gamma^3$. This choice has the virtue of lowering costs for the Proton Driver itself by reducing both the required beam energy and magnet apertures. However, the costs for the Linac and source improvements, unlike the costs for the ring components, cannot be scaled from the baseline design.

Considerations of Linac front-end improvements have been made in the main body of this report. Replacement of the Cockcroft-Walton pre-accelerators by RFQs, modifications to the initial drift tube structures of the 200 MHz Linac, and improved H^- sources are included in the PD project. These improvements are included in each model in this appendix at a cost of \$5.5M, even though improvements are not needed in all models.

Absolute costs for additional Linac and source improvements needed for some models have been included in the studies below by using estimates based on past experience. The Fermilab Linac energy upgrade done in 1992 cost about \$2M for each 40 MeV module. In the studies below we have assumed an inflation-adjusted cost of \$2.67M per 40 MeV. This might be somewhat conservative in that one might expect 50 MeV from a module built today. A combination of pulse length and beam current improvements is needed for the H^- source to provide all that is required for the cases in the studies. Where more than 3×10^{13} protons are needed from the Linac, a rather arbitrary figure of $2M for a source improvement program has been added. It is assumed that the source can be improved to provide the required number of protons within the present Linac pulse length of ~100 μs such that improvements to the Linac pulse forming networks will not be needed.

An additional benefit from increased injection energy is higher injection velocity. This reduces the frequency range of the rf system and perhaps, therefore, the cost of the Finemet system. While $\Delta f/f = 2(f_{ext} - f_{inj})/(f_{ext} + f_{inj}) = 33\%$ for the bPD, it is only $\Delta f/f = 13\%$ for the 8 GeV model with $T_{Linac} = 0.73$ GeV. While it is not clear that this reduced frequency swing would eliminate the need for the bPD 7.5 MHz rf tuners (roughly a $10M item), it would surely help if ferrite systems of a more conventional sort were chosen because of power considerations.

B.2.4. Apertures

The magnet good-field aperture usually defines the machine acceptance at the injection energy. In the 16 GeV baseline Proton Driver design, the aperture is such that a beam of $\varepsilon_N = 60\pi$ mm-mr is accepted. This is larger than the 40π acceptance that the MI was designed to have at 8 GeV. While this may have some consequences for MI extraction and beam transport, there is no problem with injection into the MI from the bPD at 12 GeV since the 60 π beam emittance will be reduced by the adiabatic damping factor $\beta\gamma$.

One reason the bPD must have a 60π acceptance is that it has a circumference that allows only 4 batches to be stacked in the MI. With only 4 batches, it is necessary to have at least 3×10^{13} protons per batch to reach the 1.2×10^{14} MI requirement. Thus the normalized emittance was increased from 40π to 60π to keep the Laslett tune shift fixed as the needed intensity increased from 2×10^{13} to 3×10^{13}.

However, by reducing the PD circumference to that of the present Booster (C_B), one can inject 6 batches each with 2/3 the number of protons into the MI and provide the same total intensity with $\varepsilon_N = 40\pi$ and the same Laslett tune shift as in the baseline PD. To reduce the circumference T_{max} must also be lowered.

To satisfy the Stage 2 requirement of 1 MW on target with a machine with lower top energy it is necessary to inject more protons. Larger N_P increases the Laslett tune shift unless the normalized emittance can be increased the same fraction. The algorithm used in the spreadsheet studies is to increase the Linac energy so that $\beta^2\gamma^3$ makes up for the increase in protons.

A major advantage in using a smaller magnet aperture is the reduced cost for the magnet and power supply systems. The costs of magnets, chokes, and capacitors in the resonant system are proportional to the stored energy in the ring magnets,

$$\text{Stored Energy} = k \sum_{\text{magnets}} (B_{max}^2\, L\, A_T) \tag{B.2}$$

where B_{max} is the maximum magnetic field, L the effective length, and A_T is the transverse aperture of each magnet. A_T depends on a combination of the acceptance requirements for the needed beam emittance and the momentum acceptance. For injection, only a few mm of momentum acceptance are needed and the geometric aperture is primarily determined by ε_G. At extraction energies, large momentum acceptance is needed to allow short bunches to be formed. In this case, the horizontal emittance is damped by the $\beta\gamma$ adiabatic damping factor such that when the momentum excursion is added, the total beam size fits within the acceptance determined by the injection requirements.

An assumption in the baseline PD design is that the present Booster 53 MHz rf cavities will be used to provide Stage 1 acceleration for MI use. While the reuse of these cavities reduces Stage 1 costs, it does limit the 16 GeV ring to operation at 12 GeV and it also precludes simultaneous operation of the PD and Booster. Perhaps a more significant problem is that the 2.25" diameter aperture of these cavities is thought to limit the ~ 20π acceptance of the present 8 GeV Booster. The PD design acceptance and circumference determine the amount the cavity bore will have to be increased. Tests of a modified Booster cavity with a 5" diameter bore suitable for the baseline 16 GeV PD with 60π emittance are now underway. Although no problems are envisioned with this upgrade, it might be facilitated by using an rf cavity bore diameter of 3.8", which an 8 GeV 40π ring with present Booster circumference would require.

B.3. First study: Cost as a function of T_{max}

To study the cost drivers for the two construction stages, hypothetical Proton Drivers of 8, 12 and 16 GeV maximum kinetic energy (T_{max}) have been modeled. A magnet with fixed geometric transverse acceptance of 40π mm-mrad is used. This acceptance was chosen because it is the design acceptance of the MI, it seems adequate to satisfy the performance requirements, and using a single number for all three energies simplifies the comparison of other variables. Another variable, which is held constant for the first two studies, is the maximum dipole field of 15 kG used in the baseline design. Note that while the kinetic energy is traditionally used for the description of machines at Fermilab, the momentum is the true scaling variable, where $P_{max} = \Sigma_{dipoles}(BL)$. The ratio of momenta for the nominal 16 and 8 GeV rings is 1.9.

The variables to be used to satisfy the performance requirements for the three different energies are then the machine circumference and the Linac and H^- source parameters of number of protons and injection energy. The circumference is chosen to maximize the number of batches to be injected into the MI while keeping the packing fraction reasonable. For the three energies of 8, 12, and 16 GeV, circumferences of 3/4, 1, and 1.5 C_B, respectively, seem reasonable, where $C_B = 2\pi \times 75$ m is the circumference of the present Fermilab Booster. The Linac parameters are more debatable in that considerable source development will be needed to achieve Stage 2 for the 8 GeV case, although Stage 1 for that energy serves the MI well because of the larger number of batches that can be injected. Increasing the Linac energy seems rather straightforward, and space for this has been allocated in the bPD design.

It is important to note that the 16 GeV Proton Driver considered in this part of the Appendix is not the same as the baseline PD, which has an acceptance of 60π. Note also that the costs of the Stage 1 baseline PD in the spreadsheet include only the power supply system needed to power the ring to 12 GeV.

The costs used in the baseline PD are used to scale costs and performance for these machines. The cost of a machine is assumed to be made up of things proportional to: 1) stored energy (magnets and power supplies, ½ utilities), 2) rf volts per turn (cavities and their supplies), 3) tunnel length (conventional construction, vacuum system, ½ utilities, project management) and 4) to things which do not scale (Linac Front-end improvements). When required, increased Linac energy (taken to be ~\$2.7M/40MeV module) and H^- source development (\$2M) are also included.

Table B.1 is the spreadsheet for the three-energy study. Figure B.1 shows the scaled costs for the model machines on the spreadsheet for Stage 1 (lower curve) and Stages 1 and 2 combined (upper curve). The points on the smooth curves are for the 40π models at 8, 12, and 16 GeV with circumference ¾, 1, and 1.5 C_B, respectively. The extra points at 16 GeV correspond to the baseline 60π Proton Driver. The Stage 2 cost for the bPD is higher than the 16 GeV model because of its larger acceptance. The Stage 1 cost for the bPD is shown at 16 GeV, though its magnet power supplies and reused Booster 53 MHz rf system limit it to 12 GeV. All models have the same calculated Laslett tune shift as the bPD. Stage 2 models provide 1 MW beam power. Stage 1 models inject 1.2×10^{14} into the MI, except the 8 GeV case, which provides 1.6×10^{14}. Costs do not include G & A or contingency.

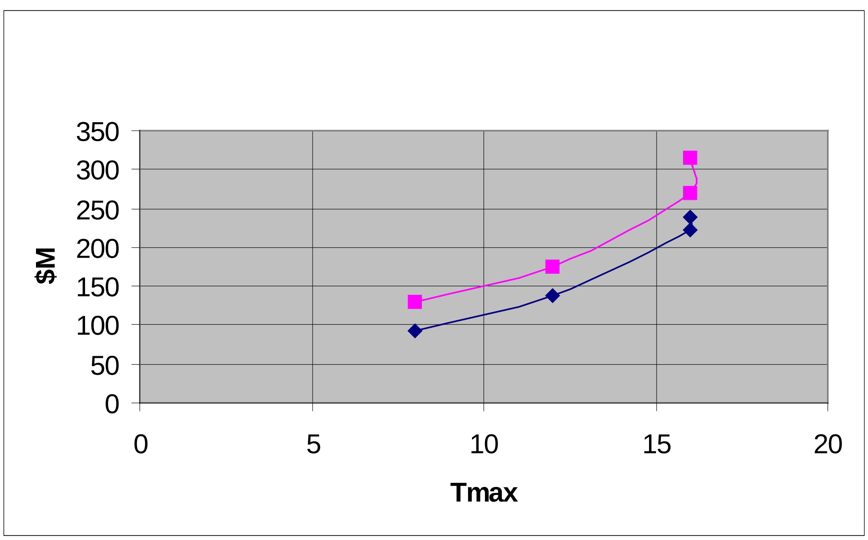

Figure B.1. T_{max} vs. Cost.

B.4. Second Study: Comparison of Operating Costs.

Here we use values estimated for the baseline PD and scale them to other machines. The magnet power supply system should require wall power proportional to the stored energy of the magnet system. The 20 MW estimated for the baseline PD magnet system seems to scale with the measured 2.5 MW of the present Booster GMPS system which has about one tenth the stored magnetic energy as the baseline PD.

The rf operating costs should scale as the number of cavities or rf Volts per turn and by the duty factor. Twenty Booster cavities operating to accelerate beam at 15 Hz require 7 MW of wall power. For Stage 1 operation with only the MI being serviced the duty factor is small. For example, with two prepulses and a PD cycle for each of the 6 batches injected into the 1.86s MI cycle, the duty factor is 8/28 = 28%, giving 2 MW of rf power. For Stage 2 operation, the 7.5 MHz rf system of the baseline PD is estimated to need 20 MW.

Figure B.2 shows the sum of the estimated annual Magnet and rf power cost needed to operate the machines discussed in Study 1. The corresponding numbers are found in the last row of Table B.1 in the spreadsheet

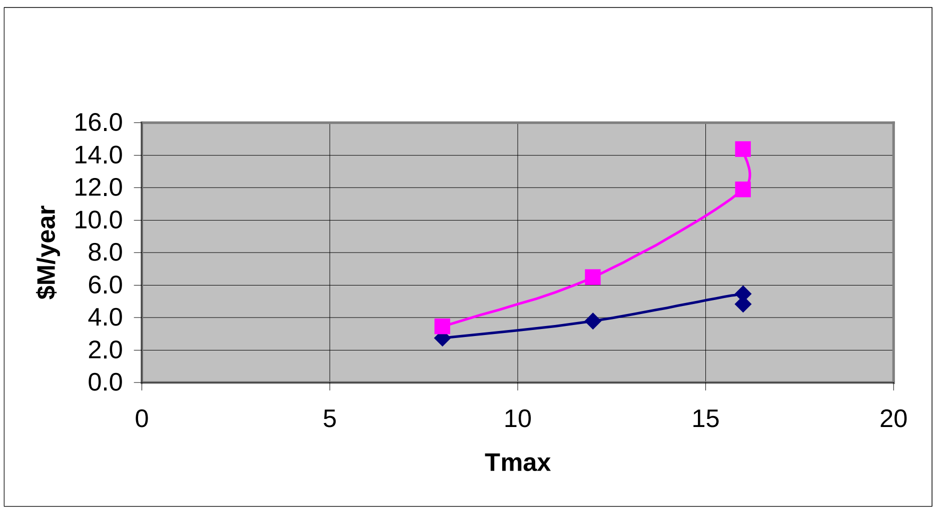

Figure B.2. Operating Expenses. The scaled annual operating power expenses for the model machines on the spreadsheet are shown for Stage 1 (lower curve) and Stage 2 (upper curve). The machine is assumed to run 80% of the time with the present electricity rate of \$0.05 per kW-h. The points on the smooth curves are for the 40π designs. The extra points at 16 GeV correspond to the baseline 60π baseline Proton Driver, although the Stage 1 value actually operates at 12 GeV.

B.5. Third Study: Cost as a function of B_{max}

Another study of interest involves a tradeoff between B_{max} and the machine circumference. In this example, the 8 GeV case from the previous study is modified by increasing its circumference to that of the present Fermilab Booster. The reduced packing fraction from this ring enlargement allows longer magnets and a lower B_{max}, even though this reduces the number of batches that can be injected into the MI and also increases the cost of rf. Since B_{max} affects costs of magnets and power supplies quadratically, one should still win by lowering B_{max} although at a reduced, but acceptable, level of performance.

An additional motivation for this study at 8 GeV is the issue of compatibility of the new Proton Driver with existing Booster functions. For normal Tevatron Collider operations, special 8 GeV Booster beam cycles are interleaved with other cycles in order to tune up the parameters for the transfers between the 8 GeV Antiproton Accumulator and the MI. To supply such cycles with a higher-energy machine will require extracting on the ramp or using the PD in a dedicated 8 GeV mode.

Table B.2 is the spreadsheet for the 8 GeV B_{max} study. Figure B.3 shows the scaled costs for Stage 1 (lower curve) and for the combined Stages 1 and 2 (upper curve) for the three choices of B_{max}. Indeed, lowering B_{max} does compensate for higher rf and construction costs. For a real design with these parameters, however, complications of a lattice that avoids transition may require a smaller packing fraction.

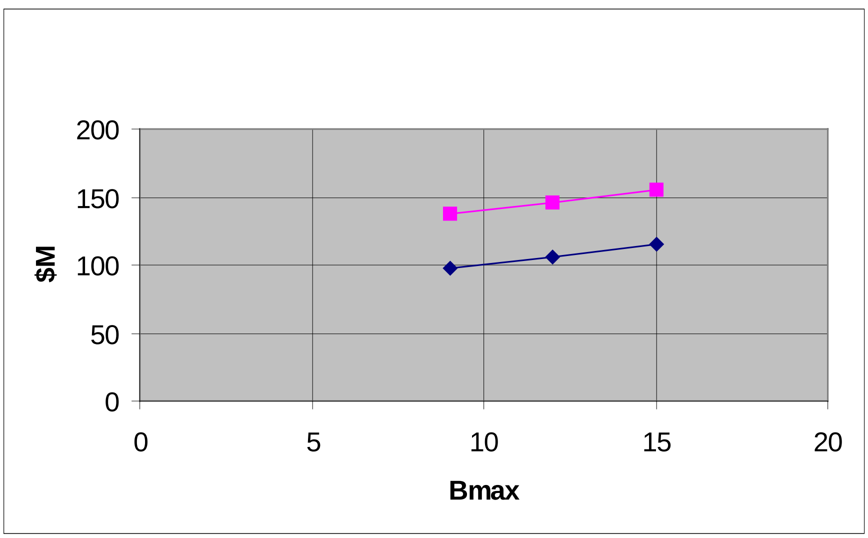

Figure B.3. B_{max} vs. Cost. The construction cost for an 8 GeV PD with Booster circumference is shown as a function of the maximum field of the dipoles. Compare these costs with the 8 GeV model with $C = 3/4\ C_B$ of Figure B.1. The smaller stored energy costs for lower B_{max} can offset the higher rf and conventional construction costs of a larger circumference. The packing fractions for the 9, 12, and 15 kG cases are 0.44, 0.33, 0.26, respectively. At B_{max} = 10 kG the cost is roughly the same as the smaller circumference machine at 15 kG. In this model, the packing fraction is 0.4 at 10 kG, compared to the bPD, 0.33, while the Stage 2 rf has one third as many cavities as the bPD in a ring with 2/3 the circumference. That is, since the fraction of the circumference occupied by rf is less in the smaller, lower energy ring, the magnetic packing fraction can be larger.

Table B.1. Construction and Operation Costs versus T_{max}

Machine		baseline PD		3/4CB, 8 GeV		CB, 12 GeV		1.5CB, 16 GeV	
stage		1	1&2	1	1&2	1	1&2	1	1&2
T_{max}	GeV	12	16	8	8	12	12	16	16
C	/CB	1.5	1.5	0.75	0.75	1	1	1.5	1.5
N	E13	3.0	3.0	2.0	5.2	2.0	3.5	3.0	2.6
T_{linac}	GeV	0.4	0.4	0.4	0.73	0.4	0.572	0.523	0.475
Acceptance	π mm-mr	60	60	40	40	40	40	40	40
N Emit	π mm-mr	61	61	41	59	41	50	48	45
batches		4	4	8	8	6	6	4	4
N MI	E14	1.2	1.2	1.6	4.2	1.2	2.1	1.2	1
Power	MW	0.86	1.15	0.38	1.00	0.58	1.00	1.15	1.00
Laslett tune	spread/bPD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B_{max}	kG	11.45	15	15	15	15	15	15	15
L_{mag}	m	236	236	124	124	180	180	236	236
E_{stored}	/bPD	0.582	1.000	0.248	0.248	0.415	0.415	0.667	0.667
rf factor	/bPD		1.000	0.244	0.233	0.496	0.488	0.992	0.995
packing fraction			0.334	0.351	0.351	0.382	0.382	0.334	0.334
Costs separated by scaling factors									
~E_{stored}	\$Mags	69.4	69.4	17.2	17.2	28.8	28.8	46.2	46.2
~E_{stored}	\$PS	61.0	85.6	21.2	21.2	35.5	35.5	57.1	57.1
~rf factor	\$RF	12.9	65.2	3.1	15.2	6.4	31.9	12.8	64.9
~C	\$Civil	86.5	86.5	43.2	43.2	57.7	57.7	86.5	86.5
~T_{linac}-.4	\$$E_{linac}$	0.0	0.0	0.0	23.9	0.0	13.4	10.2	7.0
constant	\$LFE	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Total Cost	**\$M**	238	315	93	129	137	176	221	270
Operating Power MW		13.8	41.0	7.8	9.9	10.8	18.5	15.6	33.9
\$M/Year	**@5¢/kW-h**	6.0	18.0	3.4	4.3	4.7	8.1	6.8	14.8

Table B.1 is the spreadsheet used to calculate the costs of alternative Proton Drivers. <u>Columns</u> show the parameters and costs for the baseline Proton Driver (bPD) and for 3 other model machines at 8, 12, and 16 GeV but with smaller transverse acceptance and different circumference, C. Each model has a column for Stage 1 and a column for Stages 1 and 2 combined. <u>Rows</u> are the maximum kinetic energy (T_{max},), the machine circumference (C) in units of the Booster circumference (CB), the number of protons in the ring (N_P), the injection energy (T_{linac}), the number of protons injected into the MI (N_P MI), and the MW on target. Three entries are normalized to the same parameter defined by the bPD: the Laslett tune shift, the energy stored in the ring magnets (E_{stored}), and the rf volts/turn (rf factor). The packing fraction is the ratio of the effective lengths of all the dipoles in the ring (L_{mag}) divided by the circumference. The costs of the bPD from Appendix A are separated according to how they should scale and then entered appropriately. The rows are labeled to indicate proportional to energy stored in the dipoles (~E_{stored}), proportional to volts/turn (~rf factor), proportional to circumference (~C), proportional to added Linac energy (~T_{linac}-0.4), or a constant addition. The entries for the model machines on these rows come from multiplying the bPD costs by the scaling factors.

Table B.2. Costs of an 8 GeV Booster-sized Ring as a function of B_{max}

Machine		**bPD, 3/2 CB, 16 GeV**				**C = CB, 8 GeV**			
stage		1	1&2	1	1&2	1	1&2	1	1&2
T_{max}	GeV	12	16	8	8	8	8	8	8
C	/CB	1.5	1.5	1	1	1	1	1	1
N	E13	3.0	3.0	2.0	5.2	2.0	5.2	2.0	5.2
T_{linac}	GeV	0.4	0.4	0.4	0.73	0.4	0.73	0.4	0.73
Accept	π mm-mr	60	60	40	40	40	40	40	40
N Emit	π mm-mr	61	61	41	59	41	59	41	59
batches		4	4	6	6	6	6	6	6
N MI	E14	1.2	1.2	1.2	3.1	1.2	3.1	1.2	3.1
Power	MW	0.86	1.15	0.38	1.00	0.38	1.00	0.38	1.00
Laslett tune spread/bPD				1.00	1.00	1.00	1.00	1.00	1.00
B_{max}	kG	11.45	15	**9**	**9**	**12**	**12**	**15**	**15**
L_{mag}	m	236	236	207	207	155	155	124	124
Estore	/bPD	0.582	1.000	0.172	0.172	0.229	0.229	0.286	0.286
rf factor	/bPD		1.000	0.325	0.311	0.325	0.311	0.325	0.311
packing fraction			0.334	0.439	0.439	0.329	0.329	0.263	0.263
Costs separated by scaling factors									
~E_{store}	$Mags	69.4	69.4	11.9	11.9	15.9	15.9	19.8	19.8
~E_{store}	$PS	61.0	85.6	14.69	14.69	19.59	19.59	24.49	24.49
~rf factor	$RF	12.9	65.2	4.2	20.3	4.2	20.3	4.2	20.3
~C	$Civil	86.5	86.5	57.7	57.7	57.7	57.7	57.7	57.7
~T_{linac}-.4	$Elinac	0.0	0.0	0.0	24.0	0.0	24.0	0.0	24.0
constant	$LFE	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Total cost	$M	238	315	97	137	106	146	115	155
Operating	MW	13.3	41.0	5.16	9.82	6.36	11.02	7.56	12.22

Table B.2 is the spreadsheet used to calculate the costs of model Proton Drivers at 8 GeV with Booster circumference but different maximum dipole fields. The columns show the parameters and costs for the baseline Proton Driver (bPD) and for model machines with 9, 12 and 15 kG B_{max}. All definitions are the same as in Table B.1.